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AN APPARATUS AND METHOD FOR MANIPULATION OF AN OBJECT

FIELD OF THE INVENTION

The present invention relates generally to micromechanical systems, and more particularly to an apparatus and method for manipulating an object.

BACKGROUND

Microassembly provides the capability to construct three dimensional heterogenous microsystems by joining sensors, actuators, structures, and intelligence. Such components are separately fabricated and ideally available off the shelf.

The problem of robotic microassembly has been explored using high precision actuators and vision feedback. Vision based approaches are limited by poor depth of field of high power microscopes, cluttered views, and lack determination of contact or contact forces. In addition, it is difficult to perform several distinct operations in parallel as microscopes are quite bulky and expensive (although parallel operations can be performed with rigid pallets and fixtures). Alternatively, force sensor based approaches can be local and provide exact information about contact between surfaces.

At the micro-scale level, adhesion forces of surface tension, and electrostatic and Van der Waals force dominate gravitational forces. Recent work has shown how adhesive forces can be used advantageously during microassembly tasks by controlling contact areas and surface tension, to ensure that microparts are reliably transferred to the target surface and released from a gripper.

Previous micromanipulation work has used a single probe or parallel jaw grippers to manipulate parts. The parallel jaw gripper approach follows from macro-robotics where a simple gripper is used with a six degree-of-freedom (DOF) arm to reorient and position parts. However, sub-centimeter six DOF micro-robot arms are not yet available.

SUMMARY

In one aspect, the invention features an apparatus to manipulate an object. The apparatus comprises a pair of actuated compliant beams, mounted substantially perpendicular to each other, which can grip and manipulate the object.

Various implementations of the invention may include one or more of the following features. Each compliant beam includes a piezoelectric actuator. One end of the piezoelectric actuator is attached to a proximal end of a base member. A tip member is attached to a distal end of the base member. The tip member has an inclined face configured to engage the object to be manipulated. The face of the tip member may be inclined at angle of approximately 45 degrees. A strain gauge is located at a face and back of each of the base member and the tip member. The piezoelectric actuator drives a distal end of the base member. This drive is achieved through a point contact. A tip member is joined to one end of the piezoelectric actuator. Each compliant beam includes an actuator selected from the group consisting of a thermal actuator, a motor-driven beam actuator, a polymer/thermal actuator, and a flexible circuit actuator. At least one strain gauge is provided to measure a deflection of a beam or a force applied by a beam. One of the beams is only driven along a first axis, while the other one of the beams can

only be driven along a second axis that is perpendicular to the first axis. Each beam is fixed to a surface.

In another aspect, the invention is directed to an apparatus to manipulate an object comprising a first arm and a second arm. The first arm is actuated only along a first axis, while the second arm is actuated only along a second axis that is substantially perpendicular to the first axis. The first and second arms define a space therebetween in which an object can be positioned such that the first and second arms can grip and manipulate the object.

In yet another aspect, the invention is directed to a system to manipulate an object. The system comprises a first arm that is actuated only along a first axis. The system further includes a second arm that is actuated only along a second axis that is substantially perpendicular to the first axis. The first and second arms define a space therebetween in which an object can be positioned such that the first and second arms can grip and manipulate the object. The system also includes an XYZ stage on which the object can be positioned.

In still another aspect, the invention features a method of manipulating an object. The method comprises grasping one side of the object with a first arm that is actuated only along a first axis and grasping another side of the object with a second arm that is actuated only along a second axis that is substantially perpendicular to the first axis. At least one of the first and second arms is actuated to manipulate the object.

Various implementations of the invention may include one or more of the following features. The first and second arms are actuated to roll the object. The first and second arms are

actuated to pick and place the object. The first and second arms are actuated to reorient the object perpendicular to a grasping wall. The first and second arms are actuated to align the object along a wall.

In yet another aspect, the invention features a method of manipulating a submillimeter-sized object. The method comprises gripping one side of the object with a first actuated compliant beam and gripping another side of the object with a second actuated compliant beam that is mounted substantially perpendicular to the first beam. The first and second beams are operated to manipulate the object.

In yet another aspect, the invention is directed a method of manipulating an object comprising grasping one side of the object with a first beam that is actuated only along a first axis, and grasping another side of the object with a second beam that is actuated only along a second axis that is perpendicular to the first axis. The object is positioned in a groove in a wall as the object is grasped by the first and second beams. The position of the wall and the first beam is controlled such that the wall and the first beam grasp the object, while the second beam is transferred to another side of the object. The position of the wall and the second beam is controlled such that the wall and the second beam grasp the object, while the first beam is transferred to yet another side of the object. The wall is moved away from the object, and the first and second beams are operated to rotate the object 90 degrees.

Various implementations of the invention may include one or more of the following features. The steps of the above-described method may be repeated to rotate the object 360 degrees.

An advantage of the invention is that it enables the use of macro-scale dextrous manipulation techniques with simple mechanisms to reorient and position parts. By using gripping forces which exceed adhesion forces, Coulomb friction is used to control part sticking and sliding. Micro-parts, as well as larger parts, can be dextrously manipulated in an open-loop fashion (no feedback) using two one DOF arms in a plane combined with an XYZ cartesian stage.

Two-finger grasps of polygons and polyhedra will automatically slide to a stable configuration if the angle between the included faces is less than twice the friction angle. Conversely, a tangential force at one finger will cause the grasped part to roll about the opposite finger. As these grasping techniques do not require feedback, and are robust to initial conditions, they are well suited to the micro-domain and parallelization.

The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects and advantages of the invention will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

FIG. 1 is a schematic, perspective view of a system for manipulating an object including ortho-tweezers and an XYZ stage.

FIG. 2 is a schematic representation of a grasping configuration of an apparatus for manipulating an object.

FIG. 2 is a schematic representation of a grasping configuration of an apparatus for manipulating an object.

FIG. 3 is a schematic, side view of an arm of the ortho-tweezers of FIG. 1.

FIGS. 4A and 4B are views along lines 4A - 4A and 4B - 4B, respectively, of FIG. 3.

FIG. 5 is a schematic block diagram of a control system for the system illustrated in FIG. 1.

FIG. 6 is a schematic, perspective view of a monitoring system for viewing the manipulation of an object.

FIGS. 7A - 7C are schematic views illustrating a technique for rolling an object using the apparatus of the present invention.

FIGS. 8A, 8B and 8C are graphical representations of net tip deflection, estimated object orientation, and sensed force components (F_{1x} and F_{2y}) and a sensed magnitude (mag.), respectively, for the rolling of an object.

FIGS. 9A - 9E schematically illustrate a technique for reorienting an object perpendicular to a grasping plane.

FIGS. 10A - 10F schematically illustrate a technique for regrasping an object.

FIG. 11 is a schematic view illustrating an alignment technique using the apparatus of the present invention.

FIG. 13 is a schematic representations of an n x 1 array of ortho-tweezers of the present invention.

FIG. 14 is a schematic representation of an n x n array of ortho-tweezers of the present invention.

Like reference symbols and reference numbers in the various drawings indicate like elements.

DETAILED DESCRIPTION

The present invention is directed to an apparatus for manipulating an object and methods of such manipulation. The present invention will be described in terms of several representative embodiments and processes in manipulating a micro-sized object such as a sub-millimeter sized part. However, larger objects, such as sub-centimeter sized parts, can also be manipulated in accordance with the present invention, if the apparatus is scaled-up for such operation.

As shown in FIGS. 1 and 2, an apparatus 10 for manipulating an object 12 includes two actuated compliant beams or arms 14 and 16 that are mounted substantially perpendicular to each other. The beams 14 and 16 are secured to a fixed surface. For example, beams 14 and 16 can be secured to fixed blocks 18 and 20, respectively, One beam is driven or actuated along a first axis, while the other beam is driven or actuated along a second axis that is substantially perpendicular to the first axis. The perpendicular configuration of the beams 14 and 16 makes it possible, for example, to rotate the object 12 by controlling the deflection of each beam separately.

As shown schematically in FIG. 2, the beam 14 is considered to be an x-arm (Arm1). It can move or translate along the x-axis as represented by a spring element 14a. However, it is prevented from moving along the y-axis as represented by a constraint element 14b. Thus, the arm or probe 14 has one DOF and moves in the +/- x-direction. The beam 16 is considered to be the y-arm (Arm2). It can move or translate along the y-axis as represented by a spring element 16a. However, it is prevented from moving along the x-axis as represented by a constraint element 16b. Thus, the arm or probe 16 also has one DOF and moves in the +/- y-direction.

As shown in FIGS. 3, 4A and 4B, each arm or beam 14, 16 of the apparatus 10 may comprise a piezoelectric actuator 22, a base member 24 and a tip member 26. The piezoelectric actuator 22 may be a Thunder Model TH8-R (http://www.face-int.com/thunder/, Norfolk, Virginia) that has dimensions of 64 millimeters (mm) x 12.7mm x 0.5 mm. The base may be a stainless steel sheet that has dimensions of 0.18mm("t") x 63mm("l") x 13mm("w"). The tip may also be made of a stainless steel. Its dimensions may be 0.05mm("a") x 10mm("b") x 2mm("c"). The tip 26 may project a distance "d", about 6mm, from the front end of the arm base 24.

The tip compliance can be on the order of 100 Newtons per meter (N/m). As such, a deflection of 10^{-6} meters corresponds to about 10^{-4} N or 0.1 milli-N. This small force accuracy allows a part to be "tapped" with a force of about 0.4 milli-N, without altering its position, as it sits on, for instance, a low taction Gel-Pak. (See http://www.gelpak.com, GEL-Film PF-80-X0, Sunnyvale, California).

To fully grasp a part, the arms 14, 16 apply a force of about 4 milli-N. The strain gauges, discussed below, are sensitive enough to resolve a small tapping force of about 0.4 milli-N, yielding an order of magnitude difference in the forces used to sense versus manipulate.

The tip is attached to the base by, for example, an adhesive. A face 26a of the tip 26 is inclined at angle of approximately 45 degrees(°) to form a point 26b. The point 26b of the tip face 26a is that part of the beams 14, 16 that contacts the object to be manipulated. The point 26b can be formed by cutting a metal sheet, from which the tip is made, with scissors.

The piezoelectric actuator 22 and the arm base 24 are clamped together at a proximal end 24a of the arm base by, for example, a screw 28. The arm base 24 is driven with a point contact by means of, for example, a screw 30 at a distal end 24b of the arm base. The direction of movement of the tip is represented by arrows "A". The arm 14, in one embodiment, is configured such that the drive direction "A" is along the x-axis, while the arm 16 is configured such that the drive direction is along the y-axis.

Strain gauges are attached to the beams 14, 16 to measure beam deflection or a force applied by a beam. Specifically, strain gauges 32 and 34 are attached to the face and back, respectively, of the arm base 24. Another pair of strain gauges 36 and 38 are attached to the face and back, respectively, of the tip 26. The gauges on the arm base sense the overall deflection of the arm as it is driven by the piezoelectric actuator. By mounting gauges on the arm base rather than the piezo actuator, hysteresis in sensing due to actuator hysteresis

is avoided. The gauges on the tip sense the gripping force with 100 micro-N accuracy. The strain gauges on the tip of the arm 14 only sense left/right forces. They do not sense forces pressing "into" the tip orthogonal to this.

The strain gauges (1mm length x 0.15mm width) can be an Entran model ESB-020-350 (http://www.entran.com, Fairfield, NJ). The strain gauges may be glued to their respective surfaces by the adhesive of the ES-TSKITI supply kit that is available from Entran. The electrical leads 39a, 39b, 39c, and 39d for the strain gauges are connected between soldering pads 37a, 37b, 37c and appropriate cable connectors 40a and 40b.

The arms or fingers 14, 16 may be constructed in other ways. For instance, the arm base could be eliminated and the tip could be attached directly to the piezoelectric actuator. Also, other forms of actuators may be used such as thermal actuators, motor-driven beam actuators, polymer/thermal actuators, and flexible circuit actuators.

The apparatus or ortho-tweezers 10 are fixed in space above a work platform 42 that is mounted on an *XYZ* stage 44 (see FIG. 1). The stage is actuated by stepping motors in the X, Y and Z directions. A component or object 12 to be manipulated is placed on the work platform 42, and the stage is operated so that the tweezers can manipulate it. As noted, the arms 14, 16 are arranged perpendicular to each other. (Note that the arm stiffness matrix can be the same as for the one DOF arm discussed in R.S. Fearing, "Simplified Grasping and Manipulation with Dextrous Robot Hands", IEEE Journal of Robotics and Automation Vol. RA-2, No. 4, December 1986, the entire disclosure of which is incorporated herein by reference. As discussed in this paper, this stiffness matrix guarantees stable

grasps, without feedback, for polygons with the included angle between grasp faces less than twice the friction angle.)

Each arm 14, 16 of the apparatus 10 is pushed and bent by its respective piezoelectric actuator. The deflection of an arm is controlled by the voltage to the piezoelectric actuator. As noted, the strain gauges are used to measure the deflections and the forces at the arms. Each tip of the arms 14, 16 may have a range of motion on the order of .1 to 200 microns (μm).

As shown in FIG. 5, a personal computer (PC) 46, for example, an Intel Pentium, controls the operation of the overall system. A display 48 is provided as part of the control system. The voltages to the piezoelectric actuators of the arms 14 and 16 are controlled by the outputs of a digital/analog (D/A) card 50. High-voltage amplifiers 52 and 54 magnify the D/A outputs approximately 40 times and apply them to the piezoelectric actuators.

The strain gauge outputs are amplified by strain gauge amplifiers 56a, 56b, 56c and 56d, and read by an Advantech Corp. Multilab card 58. The output range of the strain gauge amplifiers may be about -10~+ 10 volts (V), while the input range of the Multilab card may be about -5V~+ 5V. Since the overvoltage of the card is +/- 30V maximum, the card will not be damaged by the output of the strain gauge amplifiers. The stain gauge outputs can be converted into deflection or force. The Multilab card 58 also controls the X, Y and Z stages of the stage 44 by six TTL signals.

A motor interface (I/F) card 60 provides a hardware interlock to prevent the stage from overrunning its limits. When it detects a limit input produced by limit switches 62a,

62b or 62c, it simply bans the output of a clock signal to the appropriate stage driver 64a, 64b or 64c.

As shown by FIG. 6, the manipulation of an object can be observed through two color cameras 66 and 68. The camera 66 is mounted on a steromicroscope 70 and shows the top view of a manipulation. The camera 68 is attached to a 30-degree-tilted stand 72 and provides a side view. The output of cameras 66 and 68 are displayed on monitors 74 and 76, respectively.

In operation, the perpendicular configuration of the arms 14, 16 makes it possible to rotate an object (around the z-axis) by controlling the deflection of each arm separately. Referring back to FIG. 2, the tip positions of arm 14 (Arml) and arm 16 (Arm2) are defined as $(x_1, 0)$ and $(0, y_2)$, respectively, and a point contact with an object is assumed. The width and orientation of the object is defined as W and θ. When the ortho-tweezers grip the midpoints of opposite sides of a square object, $x_1 = W \sin(\theta)$ and $y_2 = W \cos(\theta)$.

A component or object can be reoriented in a plane by controlling x_1 and y_2. As seen in FIGS. 7A - 7C, the passive compliance of the arms 14, 16 ensures that a part 120 remains grasped. The voltages to the arms 14, 16 are controlled, and strain gauge outputs are measured. The piezo drive voltages for the two arms are $V_1 = V \sin(\alpha)$ and $V_2 = V \cos(\alpha)$, where α is the desired part orientation. In one experiment, a solder-coated silicon component of 200μm x 100μm x 75μm was rolled in air, as represented by FIGS. 7A - 7C. In a set of initial experiments with rotation at 10 Hz, and grasping the 75μm by 100μm face of the part, the part was rolled ± 45° successfully in 42 out of 50 trials of 100 rotations. In the eight trials with failures, the

part rotated an average of 46 (min. 12) cycles before falling out of the grip. The most likely cause of failure was the part "walking" in the grasp due to asymmetries in surface friction.

The part angle estimated from arm position measurements is $\hat{\theta}_p = \tan^{-1} x_1/y_2$, where x_1 and y_2 are calculated from the measured strains at the base and tip of the arms 14, 16. The estimated part angle from arm force measurements is $\hat{\theta}_f = \tan^{-1} F_{1x} / F_{2Y}$, where F_{1x} and F_{2Y} are calculated from the measured strains at the arm tips. The normalized grasping force is $\sqrt{F_{1x}^2 + F_{2y}^2}$ which is kept about one mN through all the angles. As can be seen from FIGS. 8A - 8C, for the 200μm x 100μm x 75μm part, the estimated angles $\hat{\theta}_p$ and $\hat{\theta}_f$ change from 0 to 90° according to the commanded angle α. The hysteresis on the rotation angle is jointly caused by the hysteresis of the piezoelectric actuators and the Coulomb friction dead band at the contacts. With a one mN gripping force and assuming a largest tweezer contact area of about 20 microns (μm^2), the contact stresses would be significantly greater than 10^6 Nm^{-2}, thus dominating any dry adhesive forces.

Another experiment was conducted to confirm that the tweezers can reliably pick and place a part. A part was placed in a dent on the work platform 42 to remain within the tweezers' workspace. The dimension of the dent were approximately 400μm(D) x 200μm(W) x 30μm(H). The command angle α was kept at about 45° and the voltage was decreased for grasping and increased for releasing. After each grasp, the work platform was lowered by about 120μm in order to check whether the part was grasped in air, then raised to its original position. It took 1.24 sec to grasp (0.16s), up-and-down(0.92s) and release(0.16s)

the part. The tweezers grasped a 75μm x 100μm part face with about one mN. There were no failures in 1000 cycles of pick and place.

A part 122 can also be reoriented perpendicular to a grasping plane by adding a torque through contact with a fixed "finger", a wall 80 attached to the work platform 42 (see FIGS. 9A - 9E). First, the tweezers grip the part and the platform is positioned such that the part is over the wall (FIG. 9A). As the platform is lifted, the edge of the wall applies a torque about the contact line between the two arms 14, 16, pivoting the part (FIG. 9B). If the friction coefficients are the same at both fingers, and the sides are parallel, for a point contact the rotation will be about a fixed axis. After being tilted, the part is pushed against the wall and made perpendicular to the platform (FIG. 9C). Then, the wall pushes the opposite edge of the part horizontally (FIG. 9D) and pivots the part to the direction parallel to the top side of the wall (FIG. 9E). In the cycle (12sec.), the part pivots 180°. The tweezers grasped a 75μm x 100μm face of the part at about 1.5mN. There were no failures in 1000 cycles of 180°-pivot.

Unlike macro parts, a submillimeter-sized part strongly sticks to other objects such as the tips of manipulators. In device assembly, it is often necessary to regrasp a part for further operations such as rotation, pivot, bonding and alignment. It is possible to hold a part by vacuum, gel or another tweezer for regrasping. But it is easier to hold it without any extra devices and delicate control. A regrasping method was developed in which a part 124 was rotated more than 360° by repeating 90°-rotation.

As shown in FIGS. 10A - 10F, the part 124 is grasped by the tweezers 10 at $\alpha = 90°$ and an L-shaped wall 82 fixed on the platform stage 42 is pushed against the part. While the stage and the arm 14 (Arml) are controlled so that the wall and the arm 14 keeps gripping the part, the arm 16 (Arm2) is repositioned through coordinated motion of the XYZ stage and arms to another side of the part (FIGS. 10A - 10C). Next, the arm 14 is repositioned to yet another side of the part as the wall and the arm 16 grip the part (FIGS. 10D - 10E). Then, the wall is moved away from the part (FIG. 10E) and it becomes possible to rotate the part by 90° (FIG. 10F). By repeating the above-described operations, the part can be rotated 360°.

One cycle (about 10sec.) of 90° rotation of a solder-coated silicon block of 420μm(D) x 420μm (W) x 100μm was performed in one experiment. There were only two failures in 5000 cycles of regrasping and 90°rotation. In the two failures, the part translated in the tweezers above the edge of the wall. The wall was 125μm(W) x 100 μm(H).

Due to the lack of reliable force information, it is difficult to align a sub-millimeter part through video microscopes. Thus, parts might be broken by applying too large of a force or misaligned because of insufficient force. Consider aligning a part 126 along a plain wall 84, using the tweezers 10. The part can be simply grasped and the wall driven against the part (See FIG. 11). After the part reaches the wall, it will slide and rotate between the arms 14, 16 due to geometrical constraints and finally approximately align itself with the wall.

Although the pushing force can not be measured directly, the grasping force limits the maximum friction force between the

arms 14, 16 and the part. Therefore, the maximum pushing force can be controlled by the grasping force. (The friction between the part and the platform stage is ignored, because the grasping force ($\simeq$3mN) is far bigger than the gravity force ($\simeq$400nN) on the part.) In order to detect part alignment, the moment around Point 4 (See FIGS. 12A - 12C) was measured when a $\pm 15^\circ$ rotation command was sent. The moments around Point 4 are defined by Arml, Arm2 and the wall as M_1, M_2 and Mw, respectively. In the static situation, $M_1 + M_2 + M_w = 0$. Therefore, $M_w = -(M_1 + M_2) = F1_{xY2} - F_{2yX1}$. If the part is not touching the wall, M_w should be 0. In fact, M_w was ≈ 0 when the part is not touching the wall. M_w changes in positive and negative range according to the commanded part angle, when the part is well aligned. If M_w has a level area around 0, it indicates that the part is not touching the wall in the area of the commanded part angle. Otherwise, it means that the part is well aligned. The hysteresis of M_w is caused by the hysteresis of the piezoelectric actuators. The part was a solder-coated silicon block of 420 μm(D) x 420 μm(W) x 100 μm(H).

By combining the part rolling, pivot grasp, and regrasping methods, it is possible to control the orientation of a part. In order to demonstrate the usefulness of these dextrous micromanipulation techniques, a sample structure was made by manually attaching four micro-components with an ultraviolet (UV)-curing adhesive, Loctite 352. The size of the three base components was 75 μm x 230 μm x 400 μm, and the top small component was 80μm x 80μm x 430 μm. Parts started out flat on the platform stage, and the dextrous manipulation techniques mentioned above were used to reorient each component three-dimensionally. The adhesive was applied by dipping one edge of

each component into an adhesive drop on the stage. UV light was applied to cure the adhesive for three minutes while each component was held on the structure by the tweezers.

The ortho-tweezers include two one DOF compliant fingers or arms perpendicular to each other. Strain gauges monitor the deflections, forces and part rolling angles. The tweezers can be dextrous and robust in manipulation of submillimeter-sized parts, even without closing a sensing loop. The tweezers by themselves can pick-and-place and roll parts. With help of a few fixtures on a three DOF cartesian stage, the tweezers can reliably pivot and regrasp a part by continually applying contact forces which greatly exceed micro-scale adhesion forces. By measuring contact generated moments on the part through strain gauges, it can be determined whether the part is aligned with a wall. For the demonstration of these techniques, a structure was made by bonding four micro-parts using UV-glue. With appropriate part pallets, this assembly process could be automated.

Also, by appropriately arranging a number of tweezers 10, it is possible to operate a parallel assembly with only one *XYZ* cartesian stage. For instance, as shown in FIG. 13, an array 90 of a plurality of tweezers 10 may be arranged adjacent the work platform 42 of the stage 44 to form an n x 1 assembly for the manipulation of objects. Alternatively, as shown in FIG. 14, an array 92 of a plurality of tweezers 10 may be arranged above the work platform 42 to form an n x n assembly.

A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and

scope of the invention. Accordingly, other embodiments are within the scope of the following claims.